



Assessment of proliferation resistances of aqueous reprocessing techniques using the TOPS methodology



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ABSTRACT

The aim of this study is to assess and compare the proliferation resistances (PR) of three possible Generation IV lead-cooled fast reactor fuel cycles, involving the reprocessing techniques Purex, Ganex and a combination of Purex, Diamex and Sanex, respectively. The examined fuel cycle stages are reactor operation, reprocessing and fuel fabrication. The TOPS methodology has been chosen for the PR assessment, and the only threat studied is the case where a technically advanced state diverts nuclear material covertly.

According to the TOPS methodology, the facilities have been divided into segments, here roughly representing the different forms of nuclear material occurring in each examined fuel cycle stage. For each segment, various proliferation barriers have been assessed. The results make it possible to pinpoint where the facilities can be improved.

The results show that the proliferation resistance of a fuel cycle involving recycling of minor actinides is higher than for the traditional Purex reprocessing cycle. Furthermore, for the purpose of nuclear safeguards, group actinide extraction should be preferred over reprocessing options where pure plutonium streams occur. This is due to the fact that a solution containing minor actinides is less attractive to a proliferator than a pure Pu solution. Thus, the safeguards analysis speaks in favor of Ganex as opposed to the Purex process.

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1. Introduction

The lead-cooled fast reactor (LFR) is one of six reactor concepts included by the Generation IV International Forum in the definition of Generation IV (Gen IV) nuclear energy systems. As in other fast reactors, the hard neutron spectrum of an LFR enables efficient utilization of the fuel, since a significant amount of fertile nuclei can be fissioned by the fast neutrons. In addition, ²³⁹Pu is bred from neutron capture in ²³⁸U nuclei. Further utilization of the fuel can be obtained through recycling of actinides in the used fuel.

One of the goals established for the Gen IV systems is the assurance that they will be “a very unattractive and the least desirable route for diversion or theft of weapons-usable materials” (U.S. DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum, 2002).

In support of this goal, the current study aims at comparing the proliferation resistances (PR) of three LFR fuel cycles, involving

different reprocessing techniques. For the purpose of assessing PR on a relative scale for different reprocessing options and identifying weak links, the TOPS methodology (Technological Opportunities to increase the Proliferation resistance of global civilian nuclear power Systems) has been chosen (NERAC, 2000b).

The examined fuel cycle stages are reactor operation, reprocessing and fuel fabrication. In particular, this study covers three different reprocessing techniques; Purex, Ganex and a combination of Purex, Diamex and Sanex. Because of different compositions of the fuel, resulting from different reprocessing techniques, the properties of the fuel cycles will differ. The three cases are compared with respect to proliferation resistance in order to find the option which, among them, best fulfils the aforementioned goal. The scope of the study does not include evaluation of implemented safeguards measures, since no safeguards approaches yet exist for the rudimentary designs of the studied fuel cycles. Instead, the goal is to assess the inherent proliferation resistance of each facility in order to identify its most vulnerable segments.

Nuclear power systems may be evaluated with respect to different threats. Here, the only threat studied is the case where a state diverts nuclear material covertly. Hence, the physical protection aspect is not studied. It is also assumed that the state holds adequate knowledge in nuclear technology.

This work is largely based on previous work performed by van der Meer et al. (2010). However, the methodology used here has

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been slightly modified, and different fuel cycles have been investigated. Several other studies have also been performed previously based on the same, and other, methodologies (Baron et al., 2004; Chirayath et al., 2008; Goodman and Sprinkle, 2009; van der Meer and Turcanu, 2009). Baron et al. (2004) recommend, among other things, continued research and development leading to the use of advanced fuels containing higher actinides, such as ^{241}Am , to increase the radiation barrier and thereby increase intrinsic proliferation resistance. In Goodman and Sprinkle (2009), the authors conclude that once-through and closed fuel cycle alternatives have complementary advantages and drawbacks. Furthermore, they state that safeguards approaches for the once-through fuel cycle are well known and generally considered effective, whereas advanced separation processes under consideration pose new technical challenges for safeguards, but also hopefully new opportunities for detecting facility misuse.

2. The Gen IV systems studied

The hypothetical facility examined in this work is a 100 MW_e lead-cooled fast reactor, with associated reprocessing and fuel fabrication capabilities included on the reactor site in a separate building. The reactor power of 100 MW_e was chosen to represent a small reactor suitable for demonstrating the viability of lead cooled fast reactor technology. The fuel used in the reactor is either MOX or MOX with minor actinides (MA) incorporated in the fuel, depending on the choice of reprocessing technique. The included reprocessing options are:

- *Purex*: for U and Pu recycling only,
- *Purex together with Diamex and Sanex*: Purex with subsequent separation of minor actinides and lanthanides, which enables actinide recycling,
- *Ganex*: all actinides are extracted as a group.

Purex is a mature reprocessing technique that has been used commercially for decades. It allows for the recycling of plutonium in MOX fuel, leading to more efficient use of the material and a reduction of volume and radiotoxicity of the high level, long-lived waste.

In order to recycle also minor actinides in fast reactors, and reduce the amount of waste even further, there is a multitude of novel techniques under current development, e.g. Diamex–Sanex and Ganex. The introduction of minor actinides in fuel makes it more difficult to handle for a potential diverter, mainly due to the emissions of heat and ionizing radiation from curium.

Diamex–Sanex separates Am and Cm from used fuel and can be readily combined with a preceding Purex step. It has proven successful at a laboratory scale, and industrial implementation can be envisaged in the near future (International Atomic Energy Agency, 2008).

With Ganex, for which the development is a challenging long-term goal, U, Pu and MA are separated together as a group (International Atomic Energy Agency, 2008). Thus, no pure plutonium stream occurs, which is beneficial from a safeguards point of view.

The three fuel cycle options are treated separately and are referred to as *facilities* below.

3. The TOPS assessment methodology

As a basis for this work, an existing framework for assessing and comparing proliferation resistance is used, albeit slightly modified. The methodology was developed by a task force established by the Nuclear Energy Research Advisory Committee (NERAC) of the U.S. Department of Energy in 1999, and is here referred to as TOPS.

The TOPS task force identified a set of proliferation barriers from which the proliferation resistance of civilian nuclear power systems are evaluated, see Fig. 1.

Each of the examined facilities is divided into segments, representing the different forms of nuclear material. The segments are described in Section 3.2. Barrier strengths are evaluated for each segment, as described in Section 3.3.

3.1. Barriers

The identified set of barriers is an attempt to recognize ways to improve proliferation resistance by technology developments. Barriers impeding proliferation from civil nuclear power systems may be divided into three categories; (1) nuclear *material* properties, (2) *technical* features of equipment and facilities, and (3) *institutional* measures aimed at compensating for weaknesses in the former. Brief descriptions of the different barriers are presented below. For more thorough explanations, see the Annex to the final TOPS task force report (NERAC, 2000a).

3.1.1. Material barriers

Material barriers relate to inherent material qualities that describe to which extent the material is attractive to a proliferator.

• Isotopic

The isotopic barrier specifies the difficulty to construct a weapon from a certain material, under the assumption that it is in a favorable chemical form. Several attributes are of importance, e.g. critical mass, degree of isotopic enrichment, and generation of heat and radiation, which complicate the design of weapons devices.

• Chemical

The amount and difficulty of chemical processing required to form weapons-usable material, e.g. by separating the fissile material from contaminants, is addressed by the chemical barrier.

• Radiological

High levels of ionizing radiation arising from fissile materials, the daughter products of their decay and possible admixtures complicate diversion and handling of materials, and thereby strengthen the radiological barrier.

• Mass and bulk

Materials that are easily concealed and transported are related to large diversion risks, compared to bulky items. Dilute materials, which are required in large volumes to construct a weapon, and materials incorporated in bulky configurations (e.g. fuel assemblies) therefore strengthen this barrier.

• Detectability

Materials that are easily detectable by e.g. active or passive methods, and materials that provide unique radiation signatures that are hard to shield, increase barrier strength. However, the detectability of fissile materials must be supported by safeguards measures in order to have any effect on the proliferation resistance.

3.1.2. Technical barriers

The technical barriers represent the intrinsic technical features of facilities, equipment and processes, which obstruct proliferators' access to materials and facilities.

• Facility unattractiveness

Facilities that can produce weapons-usable materials, or those that can easily be modified to do so, have low barriers to proliferation, whereas facilities with little or no potential for modification have high barriers, being unattractive for obtaining

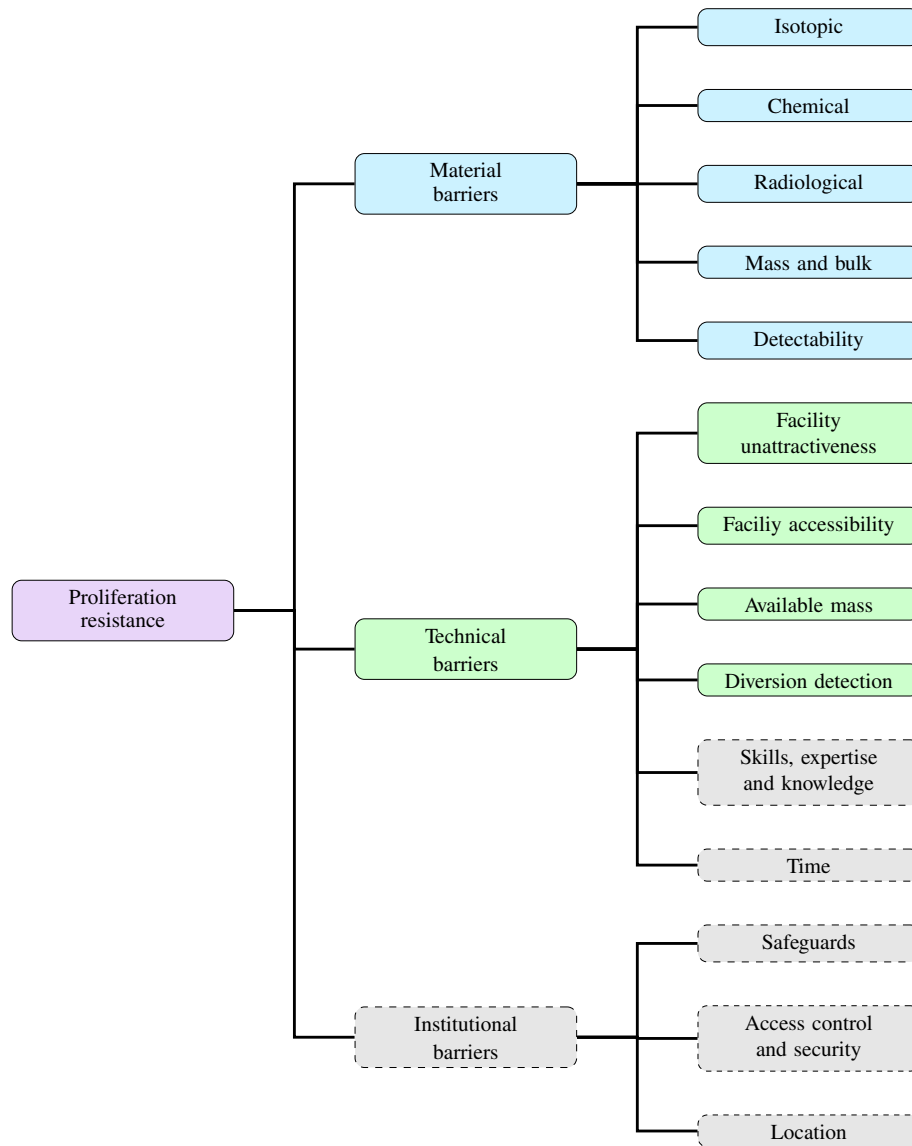


Fig. 1. Graphical overview of the TOPS methodology illustrating how the total resistance (left) is estimated based on the barrier categories (center) and barriers (right). The dashed items have been omitted in this work, see text.

material for weapons. Other attributes included in the facility unattractiveness barrier are facility throughput as well as time and cost for performing modifications.

- *Facility accessibility*

Facilities inherently restricting access to fissile material, through, e.g. remote handling operations have higher proliferation barriers than those involving hands-on access. Institutional barriers, such as security controls, are not included in this barrier.

- *Available mass*

The amount of weapons-usable materials, in direct-use form or potentially extractable, is important to a potential proliferator. Large quantities, possibly corresponding to many significant quantities, represent a low barrier.

- *Diversion detectability*

Diversion detectability refers to the detectability offered by facilities, technologies and processes themselves (as opposed to material detectability). It differs from safeguards system implementation in that it does not relate to features added

institutionally to assist in the detection of diversion. Processes which support good detection equipment and low uncertainties in the accountancy system result in strong barriers.

3.1.3. Additional barriers omitted in this work

The barrier *Skills, expertise and knowledge* has not been included in the analysis. It is considered that a state possessing the skills necessary for any type of fuel recycling in fast reactor cycles will have many insights valuable for weapons production anyhow. Furthermore, the barriers *Time* and *Location* will not give substantially different results for the three fuel cycle options. The *Access control and security* barrier is omitted since physical protection does not lie within the scope of this study. Finally, the *Safeguards* barrier is omitted, partly due to the fact that it is not expected to be any different depending on the choice of reprocessing technique. Furthermore, the *Safeguards* barrier relates to extrinsic measures such as accountancy procedures, response time of detectors and inspections, and this information is not required for an assessment of the inherent proliferation resistance of a general facility design as covered in this paper.

3.2. Segmentation

In this work, each of the three facilities is divided into *segments*, roughly representing the different forms of nuclear material occurring in each examined fuel cycle stage. The designation for all segments within each fuel cycle stage is a *segment collection* (see Fig. 2).

3.2.1. The reactor segment collection

In a reactor, nuclear materials occur in three forms:

- Fresh fuel kept in storage.
- Fuel inside the core.
- Used fuel in storage.

The fuel is either MOX or MOX + MA, depending on the case studied.

3.2.2. The reprocessing segment collection

The segments comprised in the reprocessing segment collection are:

- Used fuel in storage.
- Used fuel dissolved in nitric acid.
- Different streams of nitric acid containing the separated materials. The material streams considered in this work are U, Pu, and U + Pu + MA, depending on the chosen technique.

3.2.3. The fuel fabrication segment collection

The fuel factory involves the following segments:

- Material arriving from the reprocessing step (in either powder or sol–gel form).
- Pellets.
- Fresh fuel elements.

Again, either MOX or MOX + MA is considered in this work.

3.3. Setting values to the proliferation resistance of a facility

3.3.1. Proliferation resistance values

Proliferation resistance values, here ranging from 1 to 5, are assigned to every proliferation barrier in each particular segment. The number 1 represents a weak barrier offering very low resistance to proliferation, whereas the number 5 represents a strong

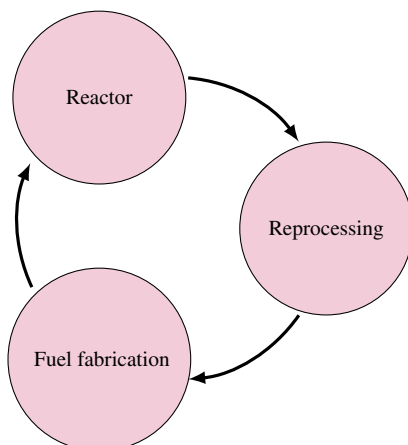


Fig. 2. The three segment collections defined in this work, each of which comprises segments where different forms of nuclear material occur.

Table 1

The chosen PR values ranging from 1 to 5 representing the different barrier strengths.

PR value	Description
1	Very low resistance
2	Low resistance
3	Medium resistance
4	High resistance
5	Very high resistance

barrier with very high proliferation resistance (see Table 1). The PR values should not be seen as absolute values of PR, but should be used merely for comparison of the different fuel cycle options.

3.3.2. Barrier weights

The barriers are not equally significant to the proliferation resistance of the fuel cycle, and need to be weighted. Therefore, the barriers within each category have been compared pairwise regarding significance to the proliferation resistance, using the Analytic Hierarchy Process (AHP). From the pairwise comparisons, a final weight is attained for each barrier. Each pair of barriers is assigned a value, according to Table 2. From these values, a matrix A is constructed. The barrier weights are then found from $Aw = nw$, where n is the largest eigenvalue of A , and w is the eigenvector associated with it. The vector w is finally normalized, such that the weights of the material barriers sum to one, as do the weights of the technical barriers. Because a detailed description of the AHP procedure is not the focus of this paper, the reader is referred to Saaty (1990) for more information.

3.3.3. Aggregation of results

For the material barriers and technical barriers occurring for each facility segment, the PR values are multiplied with the corresponding barrier weights and summed over. Thus, every segment is assigned two total resistance values; one for the material barriers and one for the technical barriers.

The most vulnerable segment per segment collection and barrier category, i.e. the segment with the lowest resistance value, is chosen as a conservative representation for the full segment collection. This means that no segment collection is considered to be more resistant to proliferation, than its weakest link.

The fresh fuel and used fuel segments are both present in more than one segment collection. Thus, if results were aggregated over the entire fuel cycle, double counting of the contributions from the fresh and used fuel would occur. In this paper, however, the reactor, reprocessing and fuel fabrication segment collections are evaluated separately to find the respective weakest links.

Table 2

Scale of measurement in pairwise comparison. Adapted from Saaty (1990).

Intensity of importance	Definition
1	Equal importance
3	Moderate importance of one over another
5	Essential or strong importance of one over another
7	Very strong importance of one over another
9	Extreme importance of one over another
2, 4, 6, 8	Intermediate values
Reciprocals	If barrier i has one of the above numbers assigned to it compared with barrier j , then j has the reciprocal value when compared with i

4. TOPS analysis of three different facilities

4.1. PR values for the segments

In Tables 3–5, the assigned PR values for the different barriers and segments are presented. The setting of the values is subject to a certain amount of subjectivity, and it may therefore be motivated to briefly describe how this was done in this work.

The isotopic barrier is strongest in the separated uranium segment, since the material contains only small amounts of fissile material. In segments containing Pu, which is classified as direct-use material, the barrier is weaker. Spontaneous emissions of neutrons and heat generation (e.g. from Cm in the MOX + MA fuels) may however strengthen the barrier.

As for the chemical barrier, in general, more steps are required to extract Pu from mixed compounds, such as MOX fuel, than from single compounds such as PuO₂ powder. Furthermore, it is considered more difficult to work with used fuel than fresh fuel, due to the emission of heat and radiation.

The radiological barrier reaches its highest value for newly discharged used fuel, which is considered self-protecting. This barrier is also rather high for segments where safety measures such as hot cells and remote handling are required.

The mass and bulk barrier is low in segments where nuclear material is present in high concentrations. It is, however, strengthened if the material is difficult to conceal and transport (e.g. mounted fuel assemblies).

Table 3

PR values for the reactor.

Barrier	Fresh MOX	Fresh MOX + MA	MOX in core	MOX + MA in core	Used MOX	Used MOX + MA
<i>Purex case</i>						
Isotopic	3	–	2	–	3	–
Chemical	2	–	3	–	3	–
Radiological	2	–	5	–	5	–
Mass and bulk	4	–	4	–	4	–
Detectability	4	–	1	–	1	–
Unattractiveness	3	–	3	–	5	–
Accessibility	2	–	4	–	3	–
Available mass	1	–	1	–	1	–
Diversion detectability	5	–	5	–	5	–
<i>Purex–Diamex/Sanex and Ganex cases</i>						
Isotopic	–	4	–	4	–	4
Chemical	–	2	–	3	–	3
Radiological	–	3	–	5	–	5
Mass and bulk	–	4	–	4	–	4
Detectability	–	4	–	1	–	1
Unattractiveness	–	3	–	3	–	5
Accessibility	–	2	–	4	–	3
Available mass	–	1	–	1	–	1
Diversion detectability	–	5	–	5	–	5

Table 4

PR values for the reprocessing plant.

Barrier	Used MOX	Used MOX + MA	Dissolved MOX	Dissolved MOX + MA	Separated U	Separated Pu	Separated U + Pu + MA
<i>Purex case</i>							
Isotopic	3	–	3	–	5	2	–
Chemical	3	–	3	–	1	1	–
Radiological	5	–	4	–	1	3	–
Mass and bulk	4	–	2	–	4	1	–
Detectability	1	–	1	–	3	3	–
Unattractiveness	5	–	2	–	3	2	–
Accessibility	2	–	5	–	3	4	–
Available mass	1	–	1	–	4	1	–
Diversion detectability	5	–	2	–	2	2	–
<i>Purex–Diamex/Sanex case</i>							
Isotopic	–	4	–	4	5	2	4
Chemical	–	3	–	3	1	1	3
Radiological	–	5	–	4	1	3	4
Mass and bulk	–	4	–	2	4	1	2
Detectability	–	1	–	1	3	3	3
Unattractiveness	–	5	–	2	3	2	3
Accessibility	–	2	–	5	3	4	5
Available mass	–	1	–	1	4	1	1
Diversion detectability	–	5	–	2	2	2	2
<i>Ganex case</i>							
Isotopic	–	4	–	4	5	–	4
Chemical	–	3	–	3	1	–	3
Radiological	–	5	–	4	1	–	4
Mass and bulk	–	4	–	2	4	–	2
Detectability	–	1	–	1	3	–	3
Unattractiveness	–	5	–	3	3	–	3
Accessibility	–	2	–	5	3	–	5
Available mass	–	1	–	1	4	–	1
Diversion detectability	–	5	–	2	2	–	2

Table 5

PR values for the fuel factory.

Barrier	MOX powder	MOX + MA powder	MOX pellets	MOX + MA pellets	MOX fuel elements	MOX + MA fuel elements
<i>Purex case</i>						
Isotopic	3	–	3	–	3	–
Chemical	2	–	2	–	2	–
Radiological	2	–	2	–	2	–
Mass and bulk	2	–	2	–	4	–
Detectability	3	–	3	–	4	–
Unattractiveness	5	–	5	–	3	–
Accessibility	2	–	2	–	2	–
Available mass	1	–	1	–	1	–
Diversion detectability	2	–	3	–	5	–
<i>Purex–Diamex/Sanex and Ganex cases</i>						
Isotopic	–	4	–	4	–	4
Chemical	–	2	–	2	–	2
Radiological	–	3	–	3	–	3
Mass and bulk	–	2	–	2	–	4
Detectability	–	3	–	3	–	4
Unattractiveness	–	5	–	5	–	3
Accessibility	–	2	–	2	–	2
Available mass	–	1	–	1	–	1
Diversion detectability	–	2	–	3	–	5

Table 6

AHP matrix representing pairwise comparisons of material barriers, and the resulting weights.

Barrier	Isotopic	Chemical	Radiological	Mass and bulk	Detectability	Weight
Isotopic	1	3	2	4	8	0.43
Chemical	1/3	1	1/2	2	4	0.16
Radiological	1/2	2	1	3	6	0.27
Mass and bulk	1/4	1/2	1/3	1	2	0.09
Detectability	1/8	1/4	1/6	1/2	1	0.05

The *detectability barrier* is high where reliable radiation signatures are present and difficult to shield. Here, it is considered that the detectability barrier is lowest for irradiated fuel, since the multitude of radioactive isotopes will give rise to a complex radiation signature.

Unattractiveness barrier:

Processes requiring only few modifications to produce weapons-usable material, such as separation processes in the reprocessing plant and Pu breeding in the reactor core, have low facility unattractiveness barriers. The barriers are considered higher in the fuel factory segments. In the fuel factory, the resistance of fuel assemblies is considered lower than the resistances of powders and pellets, due to the possibility of replacing fuel pins with dummy pins containing fertile material. Production of fissile materials from operations on powders and pellets is considered less feasible.

The *accessibility barrier* is determined by e.g. the extent of manual vs. remote handling. Fresh fuel in storage is thus more accessible than dissolved used fuel.

Available mass barrier:

If several significant quantities of nuclear material are present in a segment, the available mass barrier is very low. This is the case for most segments in this study, with separated uranium as the only exception.

Diversion detectability barrier:

Item counting is considered more reliable than accounting for e.g. powders and solutions. Therefore, the diversion detectability barrier is considered to be higher for fuel elements than for the dissolved material in the reprocessing plant.

4.2. Barrier weights

The matrices composed of pairwise comparisons of barriers according to AHP are shown in Tables 6, 7. The resulting weights

are presented in the same tables. Similar weights for TOPS barriers were obtained with AHP in van der Meer et al. (2010).

The AHP-analysis shows that among the material barriers, the isotopic composition is considered the most important, followed by the radiological and chemical barriers. The mass and bulk barrier and the detectability barrier are considered to be the least important.

The amount of mass in the facility, together with the accessibility of the material, are the most important factors in the technical barrier group. Unattractiveness of the facility and diversion detectability are less relevant.

4.3. Resistance results

Table 8 shows the lowest resistances, i.e. the weakest links, for each barrier category and facility segment collection, according to the most vulnerable element approach described in Section 3.3.3. Here, the weights in Tables 6 and 7 are taken into account. The values in Table 8 are also illustrated in Fig. 3.

In the reactor, fresh fuel is more vulnerable than used fuel regardless of the chosen fuel cycle, due to its chemical and radiological properties and easier access. Material wise, Purex offers the lowest proliferation resistance, whereas from a technical perspective all three fuel cycles are equally resistant.

In the reprocessing plant, the pure Pu streams are the weakest links of the Purex and Purex–Diamex/Sanex reprocessing, regarding both the material and technical barrier categories. The isotopic and chemical barriers of pure Pu offer low proliferation resistance. In the Ganex case, the pure U stream and used MOX + MA fuel are instead the most vulnerable segments regarding material and technical barriers, respectively. Regarding technical barriers, used fuel elements are more vulnerable than all dissolved and separated materials, since they are considered to be more accessible. From both the material and technical perspectives, Ganex offers the highest proliferation resistance.

Table 7

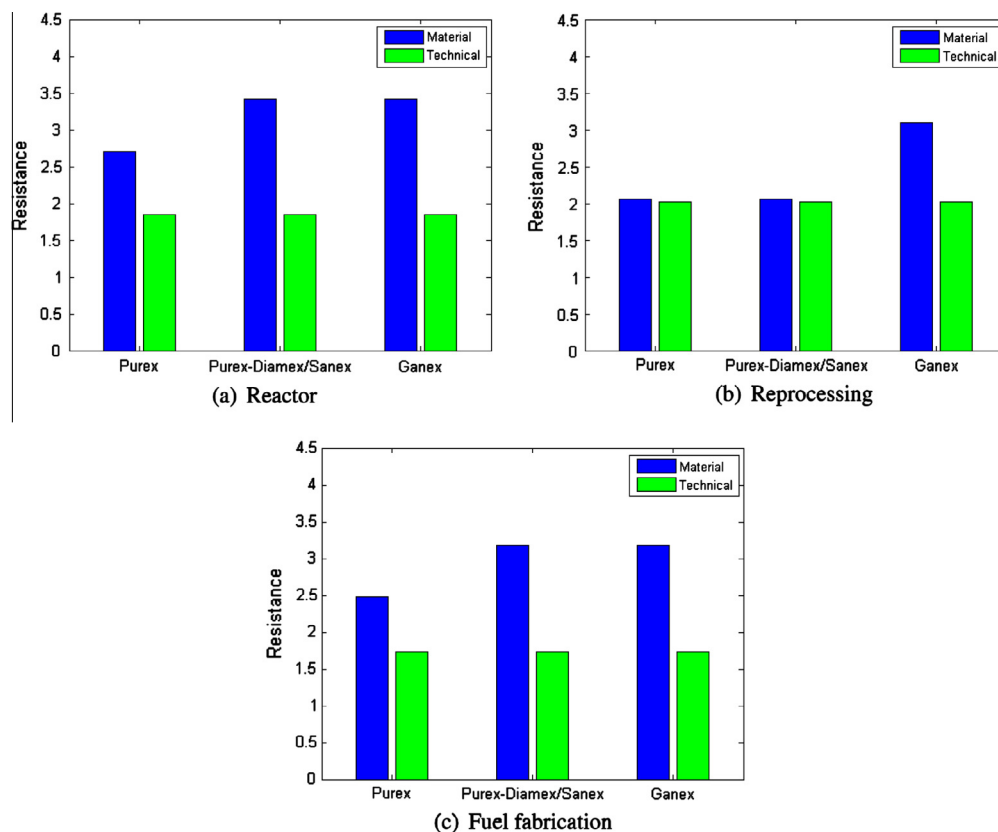
AHP matrix representing pairwise comparisons of technical barriers, and the resulting weights.

Barrier	Unattractiveness	Accessibility	Available mass	Diversion detectability	Weight
Unattractiveness	1	1/4	1/6	1	0.08
Accessibility	4	1	1/2	3	0.30
Available mass	6	2	1	5	0.52
Diversion detectability	1	1/3	1/5	1	0.10

Table 8

The lowest PR values per barrier group and facility segment collection for each reprocessing option.

Reprocessing technique	Reactor		Reprocessing		Fuel fabrication	
	Material	Technical	Material	Technical	Material	Technical
Purex	2.3	1.8	1.7	1.9	2.0	1.6
Purex–Diamex/Sanex	3.0	1.8	1.7	1.9	2.7	1.6
Ganex	3.0	1.8	2.3	1.9	2.7	1.6

**Fig. 3.** Comparison of PR values for the three fuel cycle options.

In the fuel factory, powders and fuel pellets are more vulnerable than fuel elements, since they are easier to conceal and transport, and more difficult to account for. The Purex fuel cycle is the most vulnerable material wise. The lowest technical resistance values in the fuel fabrication segment collection are the same, regardless of the chosen reprocessing technique.

5. Discussion

The strength of the TOPS methodology lies in comparing different systems to each other, with no need to evaluate absolute levels of proliferation resistance. The numbers obtained in the analysis should thus be seen merely as relative measures. TOPS is useful in the sense that the degree of detail concerning diversion threats,

facility segmentation, and proliferation barriers, may vary depending on the purpose and scope of the study.

One important drawback of the method is that it relies on subjective assumptions made by the analyst. Subjectivity can be mitigated if several experts are consulted, but their combined judgement may still be biased. Even so, when discussing safeguards approaches for new reactor types and fuel cycles, having a structured way of evaluating PR and identifying weak links in a system, such as the TOPS methodology, is valuable.

6. Conclusions

It is noted from the results of this assessment that the proliferation resistance of material barriers in a fuel cycle involving recy-

clinging of minor actinides is higher than for the traditional Purex reprocessing cycle. Isotopic and radiological properties of the different forms of MOX + MA make them less vulnerable to diversion than regular MOX.

For the purpose of safeguards, group actinide extraction should be preferred to the reprocessing options where pure plutonium streams occur. This is due to the fact that a solution containing minor actinides is less attractive to a proliferator than a pure Pu solution. If there is a pure Pu stream in the reprocessing plant, it is found to be the weakest link. Therefore there is no difference between the Purex and Purex–Diamex/Sanex bars in Fig. 3b.

Differences between the fuel cycle options regarding weakest links of the technical barrier group are seen only in the reprocessing plant, where Ganex has an advantage due to the absence of a pure Pu stream. In order to increase the technical PR values also in the reactor and fuel fabrication segment collections of Gen IV systems, the facilities should be made difficult to modify and access, and safeguards equipment should be developed to improve precision and reliability. In this way, not only the new material compositions will improve the proliferation resistance of future nuclear power systems, but also new technical solutions will contribute.

All things considered, this safeguards analysis speaks in favor of Ganex as opposed to the Purex process. The material streams of group actinide extraction are intrinsically more proliferation resistant.

In the examined facilities, several significant quantities of nuclear material are expected to be present in most parts of the fuel cycle. The available mass barrier is therefore very low in most seg-

ments. For a demonstration system containing a smaller reactor, e.g. the planned Swedish LFR concept ELECTRA with a power of 0.5 MW_{th} (Wallenius et al., 2011), together with recycling and fuel production facilities, the material throughput will be considerably smaller, with a stronger overall proliferation resistance of the system according to the TOPS methodology as a direct consequence.

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